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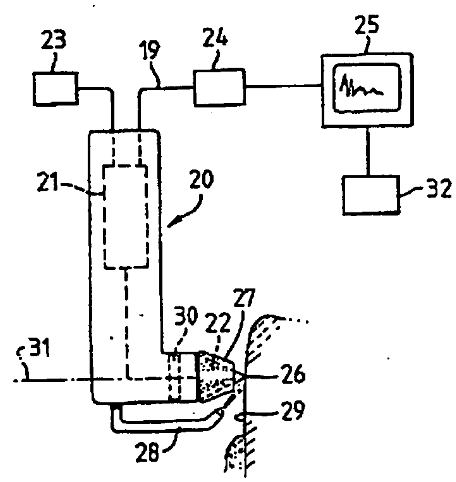

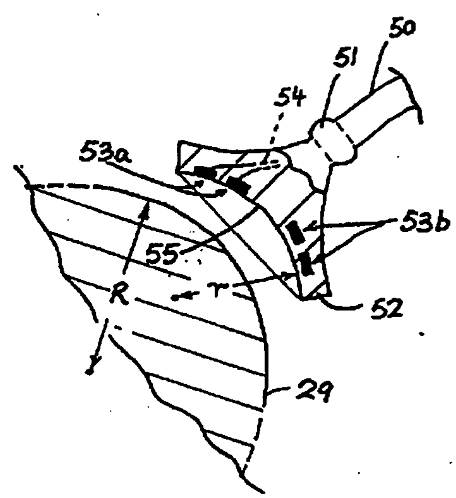

(57) Abstract

A method of and apparatus for detecting caries or other abnormality in a tooth. The tooth is contact-scanned by a probe containing one or more ultrasonic transducers, the working surface of the probe being elastic so that it can continuously change configuration to match the changing configuration of the tooth. A visual record of the ultrasonic echoes is constructed to generate regular and continuous patterns, indicative of normal interfaces within the healthy tooth, so that evident discontinuities and irregularities in the record become indicators of sites of abnormality.

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ULTRASONIC DETECTION OF DENTAL CARIES

This invention relates to the ultrasonic detection of dental caries or other abnormality. Proposals to use ultrasonics for this purpose were made at least 30 years ago - see, for instance, an article by Baum, Greenwood, Slawski _et al_. in Science 139, pages 495-496 in 1963. Many publications on the subject since then include articles by Barber, Lees and Lobene in Arch. Oral Biol. 14, pages 745-760 in 1969, and by Ng in J. Dent. 16, pages 201-209 in 1988 and in Arch. Oral Biol. 34, pages 341-345 in 1989. The latter two articles, in particular, describe addressing an ultrasonic probe to a tooth containing a known site of caries-like properties, and electronically processing the output of the probe to produce a record of VDU-type containing a feature that can be identified with the site concerned. However such prior publications do not in general teach a repeatable process which a practising dentist could use to inspect teeth which may or may not contain sites of caries, and which would enable him to determine whether such sites exist, and if so where. Nor, as a matter of detail, do such publications contain any teaching that the efficiency of the process is enhanced by deliberately allowing different values of a signal characteristic - for instance frequency - to predominate in the ultrasonic signals beamed into the tooth, and in the echo signals that are then processed to generate the visual record.

The present invention is also to be distinguished from the kind of ultrasonic detection described for example in Patent Specification EP-A-0353209, which teaches the examination of arches and other dental features by means of an array of ultrasonic transducers mounted on a single examination unit. However that unit is apparently rigid, and there is clear teaching of the need to provide a substantial pad of coupling medium between the structure under examination and the forward

face of the transducer-carrying unit which is apparently flat and rigid. The present invention seeks to provide closer contact between the tooth or other dental structure and the probe, and better correlation between the results of successive scans of the tooth by the probe, than would appear to be possible with the rigid unit and tooth/unit separation taught by such publications.

The invention is defined by the claims, the contents of which are to be read as included within the disclosure of this specification, and will now be described by way of example with reference to the accompanying diagrammatic and simplified drawings in which:-

Figure 1 is a section through a molar tooth;

Figure 2 shows a single ultrasonic probe, and associated electronic components;

Figures 3 and 4 are graphs illustrating the different frequency spectra echoes that may be obtained from sound and decayed regions within the same tooth;

Figure 5 shows mechanism by which a probe (as in Figure 2) may be held and caused to follow a predetermined route in traversing a tooth or group of teeth.

Figure 6 shows a probe including a plurality of ultrasonic transmitter/receiver units;

Figure 7 shows a molar tooth in plan, with the probe of Figure 6 addressed to the side wall of the tooth;

Figure 8 is a view in elevation of the items shown in Figure 7;

Figure 9 indicates the display of the tooth, obtainable by operating the probe as described with reference to Figures 7 and 8;

Figure 10 illustrates the use of a variant of the probe shown in Figures 6 to 8, and

Figure 11 shows a probe and tooth in section, and indicates some significant dimensions.

Figure 1 shows in vertical section taken in a plane including the line of the jaw, a molar tooth having roots 1, an occlusal surface 2, and typical enamel, dentine and pulp regions 3, 4 and 5 respectively. Line 6 indicates the typical contour of the enamel/dentine interface when seen in this section, and line 7 the corresponding contour of the dentine/pulp interface. As will be described, the present invention arises firstly from appreciating that the contours of interfaces 6 and 7 in a healthy tooth - molar or other - are typically smooth, without discontinuity or irregularity. Secondly, that it is possible to scan teeth with an ultrasonic probe so as to produce a visual record in which such an interface appears as a continuous line on the display, and so that the distance of the line from on axis of the display can be correlated with the distance between the interface and the tip of the traversing probe. The record of the echoes received from a healthy tooth will typically consist only of two smooth and generally parallel lines indicative of healthy interfaces 6 and 7. A discontinuity or irregularity in either of those lines may be presumptive of caries occurring at the respective interface. An echo from elsewhere in the tooth may be presumptive of caries within the mass of the enamel or dentine, at a range from the probe which can be deduced by comparison with the apparent ranges of the healthy parts of the tooth interfaces.

Schematically, Figure 2 shows the essential elements of a hand-held probe, for use in accordance with the present invention, and associated components. The probe 20 contains an ultrasonic transmitter/receiver unit 21, operatively connected to a "shoe" 22, mounted at one end of the probe. In use the unit 21 is energised by a power source 23, transmits ultrasonic signals towards the tooth, and an output from the unit, representing the echoes received from the tooth under scan, is processed in known fashion by electronic processing mechanism 24 to produce a VDU-type display 25. In order to produce such a record, the tip 26 of shoe 22 must be held firmly in contact with the surface of the tooth under scan, at an appropriate angle of incidence,

and traversed over it. Tip 26 must be capable of distorting elastically to conform with the changing surface configuration of the tooth: this feature will be described with reference to Figure 11. To minimise unwanted echoes and other noise within the system, shoe 22 is conveniently encased within an insulating sleeve 27, leaving only the shoe tip 26 exposed. The sleeve 27 may conveniently be of plasticine-like character, so as to adhere easily to the shoe but be deformable when required, to allow the tip 26 access to awkward crevices. Water or other suitable fluid jet means 28 are arranged to spray fluid into the vicinity of tip 26, to ensure good acoustic coupling between the tip and the surface (29) of the tooth under scan. Other media may also be used to promote good acoustic coupling, for instance fluoride or other gels, applied topically. According to the invention the probe also includes a pressure sensor 30, mechanically-coupled to the shoe 22. The sensor operates to inhibit the transmission and reception of ultrasonic signals by unit 21 unless the tip 26 of shoe 22 is being held against surface 29 sufficiently firmly, and with the probe axis 31 lying within about 10° of perpendicular to surface 29. Alternatively, or in addition, an audio-visual signal may be activated to alert a user to the fact that the sensor 30 is operating to inhibit the ultrasonic signals.

So far this specification has described how a single transducer can be addressed to a tooth and generate echoes by which interfaces of interest - for instance the enamel surface, enamel-dentine junction, pulp-dentine junction and sound tooth - decay junction - may be identified. Each echo results from an individual signal transmitted by a single transducer. The output of the display 25 will thus be of the kind known in the art as an "A-Scan", that is to say a sequence of echoes of varying amplitude, frequency distribution and "time of flight". By the latter expression I mean a time-separation on the display which equates to velocity and thus real distance within the tooth under scan. Data presented in A-Scan form may prove difficult for a practising dentist to relate to the real structure of the tooth

which he is scanning. A B-Scan display results from aggregating the A-Scan displays obtained either by moving a single transmitter linearly while it emits a succession of transmissions, or by mounting a series of transducers in line and making one transmission from each. In the art it is well understood how to present the result of a B-Scan, on a display such as item 25, in a form representing the soundness of those parts of the tooth coinciding exactly with a particular plane, that plane including the line down which the single transducer was moved or along which the several transducers of the array were mounted. Such displays may again not be easy for non-specialists to interpret, and are still likely in practice to be inadequate for a dentist, who wants to know the extent of any decay in three dimensions, not just two. This is provided by the kind of display known in the art as a C-Scan, obtainable for instance by aggregating the echoes obtained by traversing a linear array of transmitters and making a sequence of transmissions as the traverse takes place, or alternatively by mounting a plurality of transmitters in a grid-like or other two-dimensional formation.

Figure 6 shows a probe 49, usable by a dentist and capable of generating C-Scan information in the second of the two alternative ways just mentioned. A handle 50 is connected by a universal joint 51 to a flexible and elastic pad 52 on which an array, i.e. a plurality, of transducers 53, each similar to item 21 of Figure 2 and presenting an operating tip similar to item 26, are mounted in grid-like formation. Electrical input and output leads for the transducers 53 conveniently pass within the handle 50 as indicated in outline at 54. Means, not shown in Figure 6 but similar to item 28 of Figure 2, may be provided to spray couplant fluid.

As will be seen, the pad 52 of Figure 6 is roughly rectangular in outline, and of slightly dished shape. Typically such a pad would have a face area of between say 5 and 25mm^2, and carry say fifty or more of the individual transducers 53.

Possible lengths for the sides of the illustrated rectangular pad could for instance be 2mm and 3mm respectively, with each of the transducers having an area of say 200 μ^2. The pad should be flexible so that its operating face is capable of distorting to conform to match - over its entire face area - the surface of the tooth or other structure with which it is in contact at any instant during a scanning operation, but elastic so that it changes continuously to match the changing configuration of the structure as the scan proceeds, and restores to its undistorted shape when the scan finishes. Many materials, particularly silicon rubbers, already well known in the dental art, would appear to be particularly suitable, for example the silicon-based impression material marketed under the name REPROSIL by Espe GmbH. Figure 11 illustrates a feature which promotes accurate conformity between the dished working face 55 of the pad 52, and the object to be scanned, for instance the surface (29, see Figure 2) of a tooth. Considering the tooth surface as a continuous succession of areas each of convex and substantially spherical outline but of variable radius, and considering the working face 55 to be concave and of substantially spherical outline also, it may be desirable that the spherical radius r of the face 55 when at rest should be no greater than, and preferably substantially less than, the minimum spherical radius R of the surface 29. Figure 11 also illustrates alternative arrangements whereby the transducers 53 may be mounted (as at 53a) flush with the face 55 or (as at 53b) slightly embedded so that they are not visible at the surface.

Figure 7 shows in plan the simplified outline of a tooth 60 with the probe of Figure 6 addressed to the side wall 61 of that tooth ready for a transmission to begin. As has just been described with reference to Figures 6 and 11 the elastic pad 52, when in a relaxed state, is quite strongly dished in shape. When the probe is addressed to the surface of a tooth, as in Figure 7, the pad distorts so as to conform to a less strongly curved surface, and the slight resistance of the pad to this distortion

helps to promote positive contact, by way of whatever coupling medium may be provided as a thin film, between each transducer 53 and the tooth surface 61. Such coupling medium could be provided, for instance, by means such as item 28 of Figure 2. Any film of coupling medium should be as thin as is practicable, to minimise impairing the conformity between the tooth surface and the working face of the probe. Figure 8 shows the tooth and probe of Figure 7 from another angle.

Even the display resulting from a simple C-Scan of a tooth may be difficult for a dentist to interpret, because only amplitude and flight-of-time information will be used in compiling that display. What will be more useful to a dentist is a practical clinical image of the tooth in cross section, superimposed within an outline of that tooth. Such a display is possible using a probe such as item 49, on which the transducers 53 may typically be set up in an X-Y grid formation of regular separation (for example 100 µm square, possibly with a 10-50 µm separation). Each transducer in the array provides a single A-Scan with unique X-Y co-ordinates. Therefore, using the known X-Y co-ordinates of each individual transducer, and the A-Scan information of the echoes from the enamel surface (i.e. the tooth outline) and or echo-producing interfaces within the tooth, a 3-D image of the tooth outline and of all interfaces - both where sound tissue meets sound, and where sound meets decay - may be constructed.

The X-Y co-ordinates and the Z ultrasonic signal (i.e. the A-Scan signal) are limited by the physical size of, and number of elements in, the array. Ideally the pad 52 is sufficiently small to be easily manoeuvred around the tooth surface and to hug the natural surface contours, as already described with reference to Figure 7. To achieve a display of the whole tooth, using such a small probe, a composite display may need to be built up from the results of successive scans taken with the probe in successive positions against the tooth. Such positions are shown at 63 - 65 in Figure 8, and a possible display, resulting from amalgamating

the echo scans taken in those three positions, is shown in Figure 9. The processing circuitry (24, Figure 2) may itself be equipped in known fashion to inter-fit the scans from positions 63-65 by simply "recognising" the area of common echo between two scans - e.g. the cross-hatched area of overlap 66 between the scans from position 63 and 64 - and using that common area to "link" the two scans together. Alternatively the spatial relationship between successive scans may be deduced by making use of the fact that the contour of each tooth changes continuously. The pattern of distortion, imposed upon the probe 49 when addressed to the tooth at one location, will therefore change when the probe is moved to any other location. Such a pattern of distortion may be measured, for instance, by embedding strain gauges (shown in outline at 67 in Figure 8) within the flexible pad 52, and feeding their output by leads 68 to the electronic processive mechanism 24 which will be capable, by summing and analysing the strain gauge outputs from the probe in positions 63 and 64 say, to "recognise" the overlap area 66. In Figure 9 the display obtained from scans in positions 63-65 includes at least part of the tooth outline 70 (resulting for instance from pre-recorded outlines of typical tooth shapes from which the dentist can select the appropriate outline and program it into the display before he begins to scan) and indications of those regions of enamel/dentine interface and pulp/dentine junction lying directly in front of the probe positions. The scan also includes a 3-D indication 73 of part of a region of decay, which in this instance coincides with the enamel/dentine interface 71. The flat end face 74 of region 73 indicates that the three scans, taken from positions 63 - 65, have been insufficient to cover the full extent of that region: a further scan, from another position overlapping 65, would be required to achieve this.

Further alternative methods or combinations of methods, to achieve useful displays recognisable as teeth to both dentists and patients, are of course possible. For example, prior to

scanning a grid pattern could be marked upon the tooth by ink, or a fine-wire grid could actually be fitted to the tooth, so that the echo signals resulting from the scans would contain such grid pattern information which could then be used for the positional correlation of the scans. As a further alternative, as shown in outline in Figure 10, a probe could comprise transducers (not shown) mounted on a thin flexible band 80 which completely surrounds the tooth being scanned, and is pulled tight to fit closely all around the tooth wall before scanning begins.

Typically, according to the invention, unit 21 of Figure 1, and the transducers 53 of the embodiments of Figures 6 to 10, emit ultrasonic signals at a peak frequency within the range say 15-25 MHz, particularly 18-20 MHz. And it has been found that the ultrasound has typical velocities in enamel, dentine and caries of about 4100, 2750 and 1450 m/sec respectively. It has also been found that the echoes received from features - such as interfaces and caries - within the tooth typically have a peak frequency of only about 5 MHz, i.e. roughly one quarter of the peak frequency of the outgoing signal.

In practice that means that most frequencies above that 5 MHz peak value will have been filtered out, during passage through the tooth, before the echo signal reaches the transducer again. Advantages of using a transducer which emits signals with a relatively high peak frequency value include firstly improved directionality of the emitted beam. Secondly, the size required of the probe: the lower the peak frequency value, the larger the probe.

Another unexpected test result is illustrated by Figures 3 and 4, which represent the results of analysis of the frequency spectra of echo signals returned from the enamel/dentine interface and a caries site - within the dentine mass of the tooth - respectively. In these two figures the units of the X-axis are Hz x 10^7, and the Y-axis indicates the relative proportion of the total spectrum contributed by any particular frequency value. It will readily be seen that for a frequency

value of about 30 MHz upwards the spectrum values are comparable in both figures, so that there is no means of analysing them to distinguish between sound tooth and caries sites. Below 30 MHz there are considerable differences, however. For instance for X-axis values of 20 MHz in Figures 3 and 4 the Y-axis values are about 0.17 and zero respectively, and for an X-axis value of 10 MHz the corresponding Y-axis values are about 1 and say 0.8. By providing the electronic control mechanism (24, Figure 2) with the necessary algorithms to compare all echo signals with "standards" like Figures 3 and 4, at frequency values greater than say 5 MHz but less than 30 MHz, and especially around 20 MHz, considerable contrast can be demonstrated between the echoes from caries sites and sound tooth, from which clear records of the sites can be constructed.

A particular potential benefit of a method of scanning teeth, according to the present invention, is that with the addition of electronic means to store a VDU recording (extra item 32, Figure 2) a dentist can scan teeth or teeth during one session with a patient, store the result, and then scan again on successive visits and monitor the progress of caries or other abnormality by comparison with the stored record of the previous scan. However, the accuracy of such comparison clearly depends upon successive scans being performed as identically as possible. If the dentist holds and traverses the probe by hand, substantial variations in the attitude, speed of movement and route of the probe between one scan and the next are inevitable. Various ways of "fitting" successive scans together have been described with particular reference to the multi-transducer probes of Figures 6 to 9. Figure 5 shows a possible further means of fitting successive scans together, with particular reference to the single- transducer probe of Figures 1 and 2. Figure 5 shows the probe 20 of Figure 2 mounted on the rod 40 of a piston 41 mounted to move within a miniature hydraulic cylinder 42 to which the forward and return supplies are regulated by control means 43. Cylinder 42 is connected to a

clip 44 by which it may be held steady within the patient's mouth by locking over one tooth, while another tooth (45) is scanned. Control 43 causes the piston-and-cylinder combination 41-42 to traverse the tip 26 of probe 20 back and forth over tooth 45, in a direction roughly parallel to the jaw line, at a predetermined and repeatable speed, and various means - e.g. a spring-loaded connection between probe 20 and rod 40 - can ensure that the tip 26 is addressed to the tooth with sufficient force to trigger pressure sensor 30.

CLAIMS

1. A method of detecting caries or other abnormality in a tooth, including the steps of:-

contact-scanning the tooth with a probe containing a source of ultrasonic energy and capable of distorting elastically to conform with the changing surface configuration of the tooth;

receiving ultrasonic echoes from echo-producing interfaces within the tooth;

constructing a visual record of those echoes over a finite extent of the scan, sufficient to generate recognisable regular and continuous patterns, indicative of normal interfaces within the healthy tooth;

and utilising evident discontinuities and irregularities in the record as apparent indicators of sites of such abnormality.

2. A method according to Claim 1 in which the received echoes are electronically processed to produce a record of VDU type.

3. A method according to Claim 2 in which the record is of C-scan type.

4. A method according to Claim 3 in which the record includes recognisable regular, continuous and linear indications of at least one of the enamel/dentine and dentine/pulp interfaces within the healthy part of the tooth.

5. A method according to Claim 4 in which the record also includes indications of at least part of the exterior outline of the tooth.

6. A method according to Claim 4 in which irregularities in the said linear interface representations are utilized as indicative of abnormality.

7. A method according to Claim 4 in which echoes appearing on the record, at locations separated from any of the said linear interface representations, are utilised as indicative of abnormality.

8. A method according to Claim 1 in which the mean frequency of the input ultrasonic signals is substantially greater than the frequency range over which the echo signals are analysed to produce the record.

9. A method according to Claim 7 in which the mean frequency of the input ultrasonic signals lies within the range 15 - 25 MHz, particularly 18 - 20 MHz.

10. A method according to Claim 7 in which the peak frequency of the echo signals is about 5 MHz, and analysis of the echo signals concentrates upon a frequency range below 30 MHz, and especially around 20 MHz.

11. A method according to Claim 1 in which the source of ultrasonic energy comprises a plurality of individual transducers, arranged in a regular formation as a two-dimensional array.

12. A method according to Claim 11 in which the source is addressed to the tooth repeatedly in different but overlapping locations, and means are provided to identify the overlapping portions of the echoes generated by successive such operations, and thereby construct a composite visual record making use of all the echoes received in the successive operations.

13. A method according to Claim 1 in which the probe incorporates a pressure sensor operable to indicate whether or not the probe is being addressed to the tooth at an appropriate angle of incidence and/or with sufficient force.

14. A method according to Claim 1 in which the probe includes mechanical means capable of location relative to a patient's jaw and of causing the probe to traverse a chosen tooth accurately according to a predetermined pattern.

15. A method according to Claim 1 in which the visual record is stored, whereby it can be recalled for comparison with the record of a subsequent traverse.

16. A method according to Claim 5 in which the indications of the exterior outline of the tooth are provided at least in part by electronic information representing typical tooth shapes, selected and fed into the record by an operator.

17. A probe containing a source of ultrasonic energy and having a surface capable of distorting elastically to conform with the changing surface configuration of a tooth, for carrying out a method of detecting caries or other abnormality in a tooth by contact-scanning according to any of the preceding claims.

18. A probe according to Claim 17 containing strain gauges or other means which produce signals responsive to the distortion, and means to correlate such signals produced by successive but overlapping scans so as to identify the area of overlap and so enable the visual records of the successive scans to be combined.

19. A probe according to Claim 17 in which the elastically-distortable surface is concavely-curved, the minimum radius of such curvature being no greater than the minimum radius of convex curvature of the tooth to be scanned.

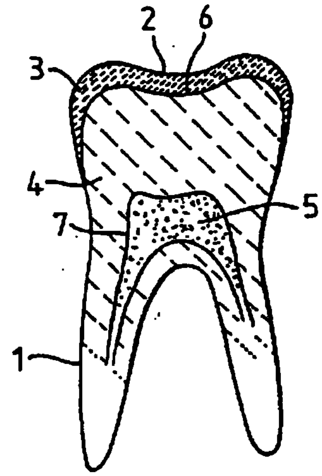

Fig. 1

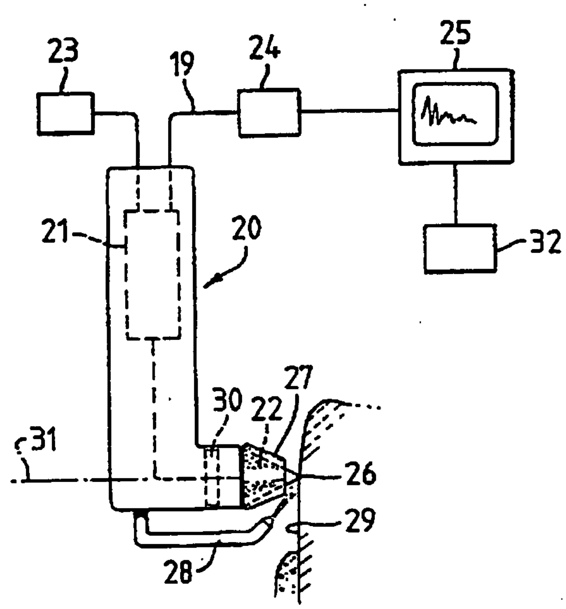

Fig. 2

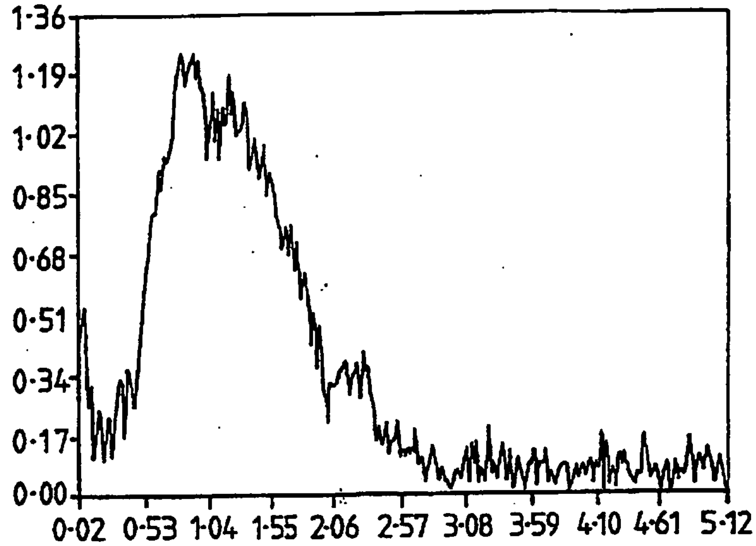
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Fig. 3

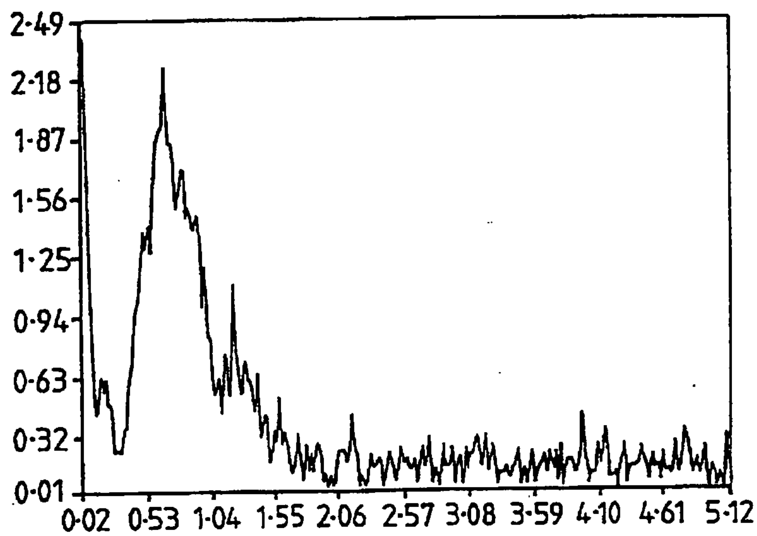
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Fig. 4

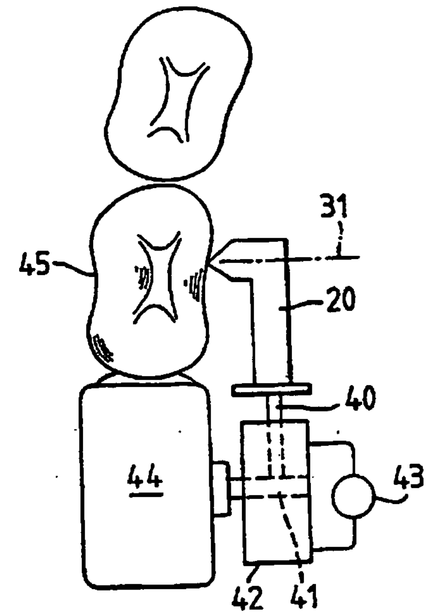

Fig. 5

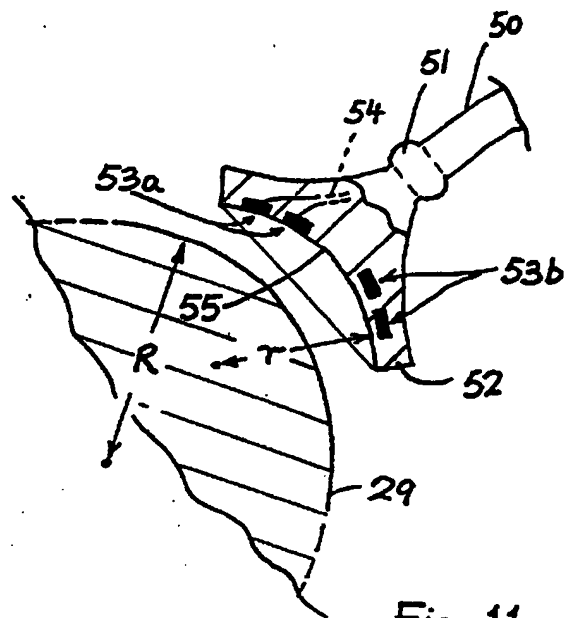

Fig. 11

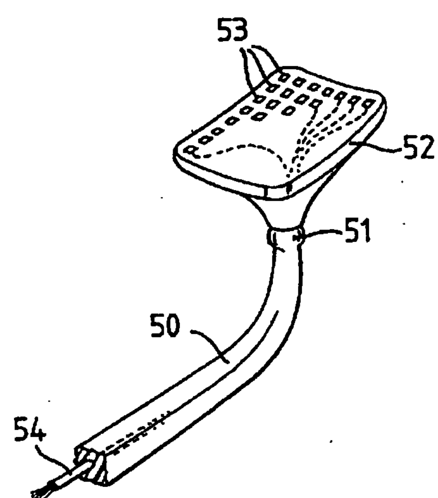

Fig. 6

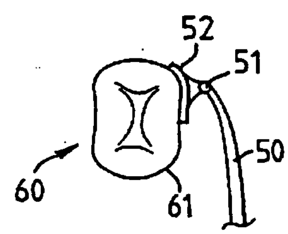

Fig. 7

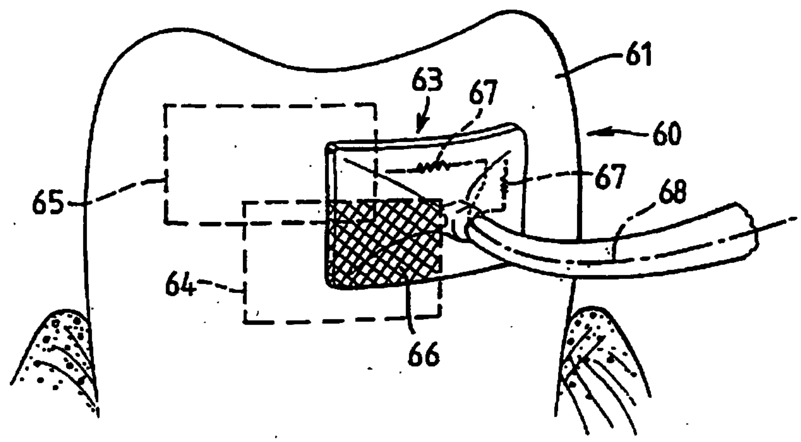

Fig.8

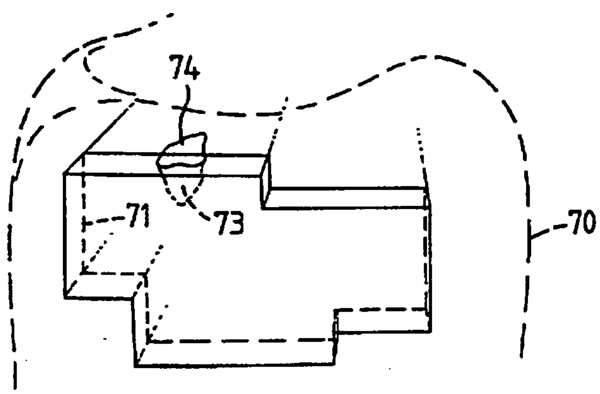

Fig. 9

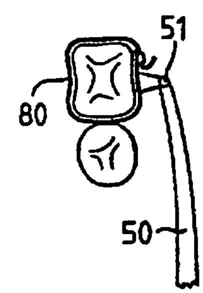

Fig. 10

INTERNATIONAL SEARCH REPORT

Intern. ...nal Application No
PCT/GB 94/01748

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 A61C19/04 A61B8/08

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 A61C A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO,A,89 03195 (HOLLMING PARMA) 20 April 1989 see abstract see page 8, line 12 - line 13; figures 1-3	1,2,17
X	EP,A,0 353 209 (GIEMMECI) 31 January 1990 cited in the application see abstract see page 2, line 61 - page 3, line 2; figures 1,3,7	1,2,11, 17

☐ Further documents are listed in the continuation of box C.

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1

Date of the actual completion of the international search	Date of mailing of the international search report
11 November 1994	22.11.94

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter. onal Application No
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